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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Alternating thrust, torque, and thrustbearing housing vibration were measured on United States Coast Guard Cutter (USCGC) KATMAI BAY during open water, brash ice, and ice breaking operations. For open water operation the propulsion system complies with all requirements of MIL-STD-167-2. Longitudinal and torsional natural frequencies of the propulsion system were identified. The statistical distribution of peak alternating thrust amplitudes due to brash ice operation was found to be skewed and therefore not normal or Gaussian.

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ABSTRACT

Alternating thrust, torque, and thrustbearing housing vibration were measured on United States Coast Guard Cutter (USCGC KATMAI BAY during open water, brash ice, and ice breaking operations. For open water operation the propulsion system complies with all the requirements of MIL-STD-167-2. Longitudinal and torsional natural frequencies of the propulsion system were identified. The statistical distribution of peak alternating thrust amplitudes due to brash ice operation was found to be skewed and therefore not normal or Gaussian.

ADMINISTRATIVE INFORMATION

INTRODUCTION

The KATMAI BAY is the first vessel of a new 140-ft WTGB class of ice breaking tugboats the Coast Guard has designed and is having built to re-place the 110-ft WYTM class. The new tugboats have a greater horsepower than the 110-ft WYTM and are larger. They also have bubbler systems to reduce friction in icebreaking.

A single four-bladed propeller 8 ft-6 in. in diameter, operating in a conventional aperture with the rudder immediately aft, drives the KATMAI BAY. The propulsion motor is directly coupled to the propeller shaft. The propulsion motor is a d.c. motor rated 2500 SHP at 245 and at 305 rpm, corresponding to the bollard speed and free route speed of the tug, respectively. Table 1 lists the nameplate data for the drive motor and thrustbearing. The shafting layout is shown in Figure 1.

DTNSRDC Full-Scale Trials Branch (Code 1536) requested the Hull and Systems Vibration Branch (Code 1962) to conduct the vibration and alter-nating torque and thrust measurements of KATMAI BAY's propeller shaft.

OBJECTIVE

The objective of this study, as stated in the Test Plan[1]* is to measure the propeller shaft alternating torque and thrust and determine the vibratory characteristics of the shafting system in open water.

APPROACH AND PROCEDURE

Measurements requested were conducted in total compliance with Military Standard 167-2 (MIL-STD-167-2) requirements; and in compliance with procedures and requirements of the Test Plan with the following exceptions:

1. Thrustbearing clearance was not recorded.

2. Due to the limited number of tape recorder channels, alternating torque and thrust, as well as vertical and athwartship thrustbearing housing accelerations, were not recorded simultaneously but recorded sequentially as phase A and B respectively (see the Instrumentation Section of the report).

3. Since the maximum longitudinal displacement response of the thrust bearing housing during open water propeller/shaft validation tests, of the first trial period, was considerably lower than the limiting levels of MIL-STD-167-2; the trials steering committee decided that vibration measurements would not be required for the second trial period. Therefore, Code 1962 was to report the results of the propeller/shaft validation test and arbitrarily select for documentation brash and level ice breaking data recorded during the first trial (29 January to 13 February 1979).

4. As stated and agreed upon, in DTNSRDC correspondence,** vibration data will be reported in the normal DTNSRDC reporting format.

INSTRUMENTATION

Code 1536 supplied and was responsible for the time code, torque, thrust and the master tape recorder on which were recorded all the measurements required by the Test Plan. Code 1962 provided the required

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*A complete listing of references is given on page 19.

**DTNSRDC letter Serial 1536:RRH 16170 - 3900/Coast Guard 1536-197-79 of 27 Apr 1979.

thrustbearing housing acceleration signals as well as instrumentation for conditioning, filtering and amplifying the alternating torque and thrust signals. Unless otherwise noted, the terms torque and thrust will be understood to mean the alternating, not mean, value. The sole purpose of Code 1962's tape recorder, oscillograph and real time analyzer (RTA) was to enable analysis of vibration data during delays and while other tests were being conducted.

A common time code was recorded on the master tape recorder and on Code 1962's (back-up) tape recorder as Channel 1. The torque and thrust signals provided by Code 1536 were sequentially passed through the same Ithaco filter (to suppress the large mean value) and through two Bur-Brown amplifiers in series and finally recorded on the master and the back-up tape recorder as Channels 2A and 2B, respectively. Thrustbearing housing vibrations were measured by using Kistler servo accelerometers and their associated amplifiers.

Vertical and athwartship accelerations were sequentially passed through the same Ithaco filter to suppress low frequency motions such as roll and heave before recording on the master tape recorder and on the back-up tape recorder as Channels 3A and 3B, respectively. Longitudinal accelerations were also filtered by an Ithaco filter and recorded on the master and back-up tape recorder as Channel 4. Figure 2 shows a schematic diagram and Table 2 lists the instrumentation used to conduct the vibration survey.

TEST RESULTS

Propeller shaft alternating torque and thrust measured during shaft validation test are plotted against exciting frequency and shaft rpm in Figures 3 and 4, respectively. Longitudinal, vertical, and athwartship displacement amplitudes of the thrustbearing housing measured during the shaft validation test are also plotted against exciting frequency and shaft rpm in Figures 5a, 5b, and 5c, respectively. Maximum values measured during the open water, shaft validation test, and during selected brash and level ice breaking maneuvers are listed in Tables 3 and 4, respectively. Figure 6 is a segment of an oscillogram of data recorded during a brash

ice maneuver. A histogram of peak alternating thrust amplitudes measured during a brash ice maneuver is shown in Figure 7.

DISCUSSION OF RESULTS

I. Shaft/Propeller Validation Tests (MIL-STD-167 Validation)

The maximum alternating torque (ΔQ) was ±10,149 ft-lb and was measured during the full-speed, full-right rudder open water maneuver. The resulting torsional stress (S_s) in the solid circular shaft of diameter (d) can be computed from Equation (1).

$$S_s = \frac{16\Delta Q}{\pi d^3} \tag{1}$$

The smallest shaft diameter, 9 in., will give the maximum stress level. Substituting into Equation (1) the values for shaft diameter (d) and alternating torque (ΔQ) gives a maximum torsional stress of ±851 psi for open water operation. Paragraph 5.1.2.1 of MIL-STD-167 sets the limit for excessive torsional stress (S_v) by the following equation.

$$S_v = \text{Ultimate Tensile Strength}/25 \tag{2}$$

Since both motor and propeller shafts are Class 2 steel forgings MIL-STD-23284 gives their ultimate tensile strength as 80,000 to 100,000 psi. Substituting into Equation (2) the value for ultimate tensile strength gives ±3,200 psi as the limiting torsional stress. Since the maximum torsional stress of ±851 psi is considerably less than the limiting stress level of ±3,200 psi of MIL-STD-167 for open water steady state, operation, the shaft/propeller system meets the limits of acceptability for Type III (Torsional) Vibration.

The lack of a peak torsional response throughout the speed range due to propeller blade excitation (blade rate) shown in Figure 3 indicates that the torsional natural frequency is above the maximum blade rate frequency of 20 Hz. The slight peak in torsional response at 23.8 Hz due to double blade rate excitation plus the randomly excited nonorder torsional

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response measured from 22.5 to 23.5 Hz are strong indications of a torsional natural frequency at 22.9 ± 0.6 Hz. This is in agreement with the 23.0 Hz torsional natural frequency computed by Westinghouse Marine Division.[2]

The maximum alternating thrust (ΔT) was ±34 percent of the mean thrust or ±14,364 pounds, and was measured during the full-speed, full-right rudder open water maneuver. Paragraph 5.2.1.1.1 of MIL-STD-167 defines the limit for excessive alternating thrust as follows. "Excessive alternating thrust occurs when the single amplitude alternating thrust, measured at the main and turbine thrustbearings, exceeds the mean thrust at that speed or exceeds 50 percent of the full power thrust whichever is smaller." Fifty percent of the full power thrust is 21,026 pounds. Since the maximum measured alternating thrust, ±14,364 pounds, is less than 50 percent of the mean thrust for that maneuver and less than 50 percent of the mean full power thrust it meets the limit of acceptability.

The maximum longitudinal vibration of the main propulsion system was ±4.9 mils (0.0049 in. at 22.9 Hz) and was measured during the full-speed, full-right rudder open water maneuver. Table I of Paragraph 5.2.1.1.2 lists the limiting displacement amplitude as ±0.020 in. from 16 to 25 Hz. Since both the maximum measured longitudinal vibration (0.0049 in. at 22.9 Hz) and the maximum measured alternating thrust are less than the limits prescribed in MIL-STD-167 the shaft/propeller system meets the limits of acceptability for Type IV (longitudinal) vibration.

Both blade rate alternating thrust and longitudinal thrustbearing housing displacement shown in Figures 4 and 5a respectively, lack any significant peaks indicative of a natural frequency below 20 Hz. The slight peak of double blade rate alternating thrust at 21.5 Hz and the randomly excited nonorder alternating thrust between 21.5 to 22.7 Hz are indicative of a longitudinal natural frequency in this frequency range.

Westinghouse Marine Division calculated[2] the lateral natural frequency of the propulsion system between 600 and 2000 Hz, well above any open water source of excitation. The maximum measured vertical or athwartship thrustbearing housing displacement listed in Table 3 is below ±2.3 mils which is low from previous experience and considered tolerable.

II. Brash and Level Ice Breaking Operation

The vibratory characteristics of the propulsion system; its natural frequencies, damping, mass and stiffness; are not influenced by brash or ice breaking maneuvers. This was verified by frequency spectra of propulsion system parameters which showed that the predominant response was at the transiently excited natural frequency or blade rate. However, the magnitude of the response; i.e., vibratory accelerations, is proportional to the transient loads at the propeller, usually indicated by the measured alternating torque and thrust. Since frequency spectra present values which are averaged, they would not be a good indication of transient signals. Therefore oscillograms of the alternating thrust or torque and acceleration at the thrustbearing housing, such as the one shown in Figure 6, were visually analyzed for peak transient or maximum values which are presented in Table 4. The alternating thrust trace of this oscillogram was compared with an oscillogram of the same unfiltered data. No difference in amplitude could be detected, therefore, the effect of the electronic filter was insignificant.

However, all oscillograms of the brash and level ice breaking maneuvers exhibited the same characteristic transient response shown in Figure 6. The transient gradually builds up and then decays, instead of the usual initial peak followed by uniformly diminishing amplitudes. This behavior has also been observed on the USCGC POLAR STAR, and has been concluded to indicate that the shafting system itself is acting as a mechanical filter and attentuating the transient loads at the propeller. Therefore, the alternating torque and thrust values in Table 4 are not respresentative of the maximum transient load at the propeller.

There are no known limits of acceptability for vibration or alternating torque or thrust under the transient loading experienced during brash and ice breaking maneuvers. The derivation of such limits is not within the scope of this study. However, it should be noted that, except for the alternating thrust, all the values listed in Table 4 are within the limits of MIL-STD-167. Unfortunately this cannot be used as a basis

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for acceptability, because the values in Table 4 cannot be guaranteed to be representative of the most severe loads the system will experience.

Figure 7 shows a histogram of peak alternating thrust amplitudes measured during a brash ice maneuver (Run 4300). Also shown are the values for the sample mean $(\bar{x})$ ($\pm 15,404$ pounds) of the peaks, and the standard deviation(s) of the peaks. The normal (no impulse, steady state) blade rate thrust is $\pm 5,270$ pounds. However, the mean value of the peak due to impulsive loads is $\pm 15,404$ pounds or three times the normal brash ice blade rate thrust, and the largest value measured was $\pm 60,948$ pounds or eleven and one-half times greater than normal blade rate thrust. Unfortunately the distribution is clearly skewed and is not normal, therefore, estimates of the higher population percentiles is not possible until the distribution is identified.

CONCLUSIONS

The following conclusions are drawn:

1. For the open water operation, the propulsion system complies with all the requirements of MIL-STD-167-2.

2. A torsional natural frequency of the propeller shaft system lies between 22.5 and 23.5 Hz.

3. The longitudinal natural frequency of the propeller shaft system lies between 21.5 and 22.7 Hz.

4. The impulse wave form of the alternating thrust and torque indicate that the propeller shaft is attenuating the transient loads acting at the propeller.

5. The histogram of peak alternating thrust amplitudes due to brash ice operation is skewed and not a normal or Gaussian distribution.

6. Because no vibration standards or criteria exist for brash ice or ice breaking operations, no conclusion may be drawn as to the propulsion systems adequacy for these operations.
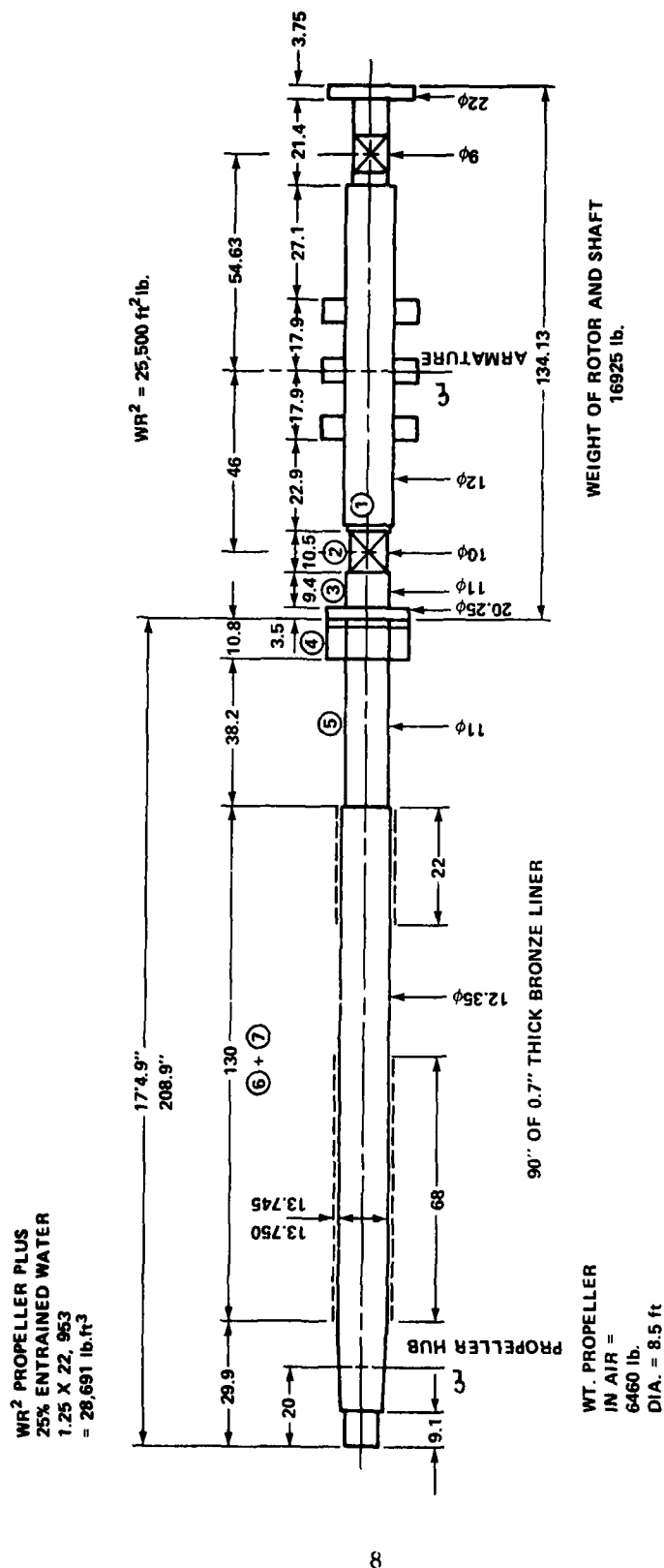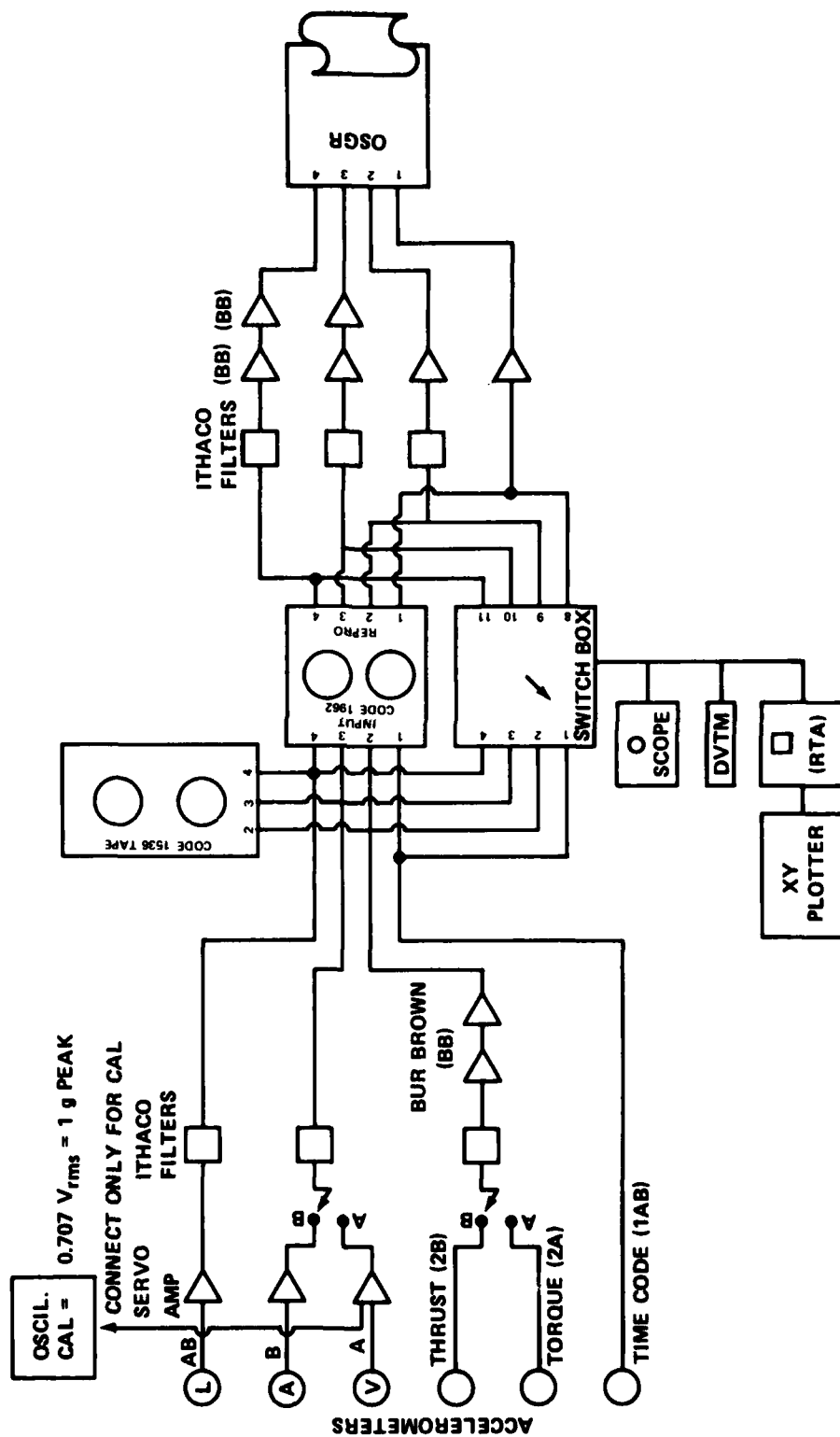
Figure 1 - Shafting Layout—140-Foot WTGB

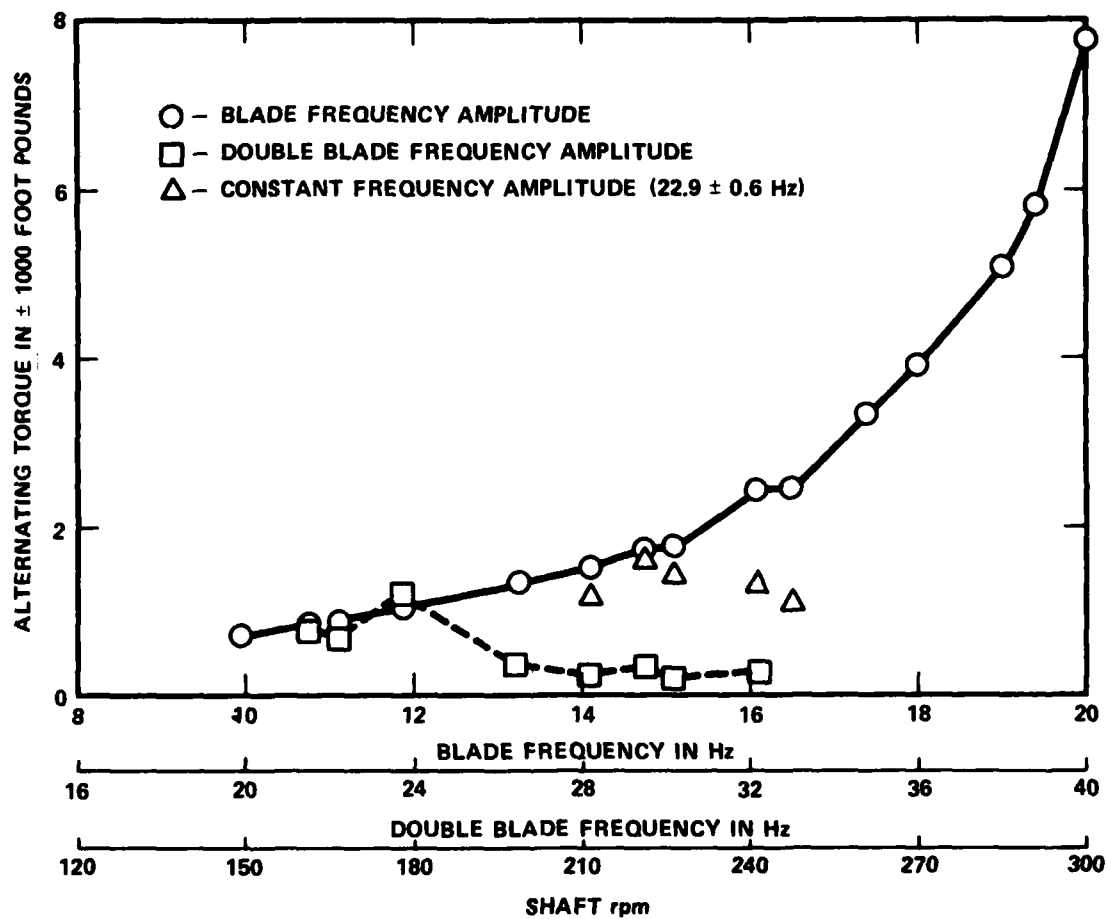Figure 2 – Schematic of Shaft Validation Test Instrumentation

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Figure 3 – Alternating Torque Measured during Open Water,
Shaft Validation Test

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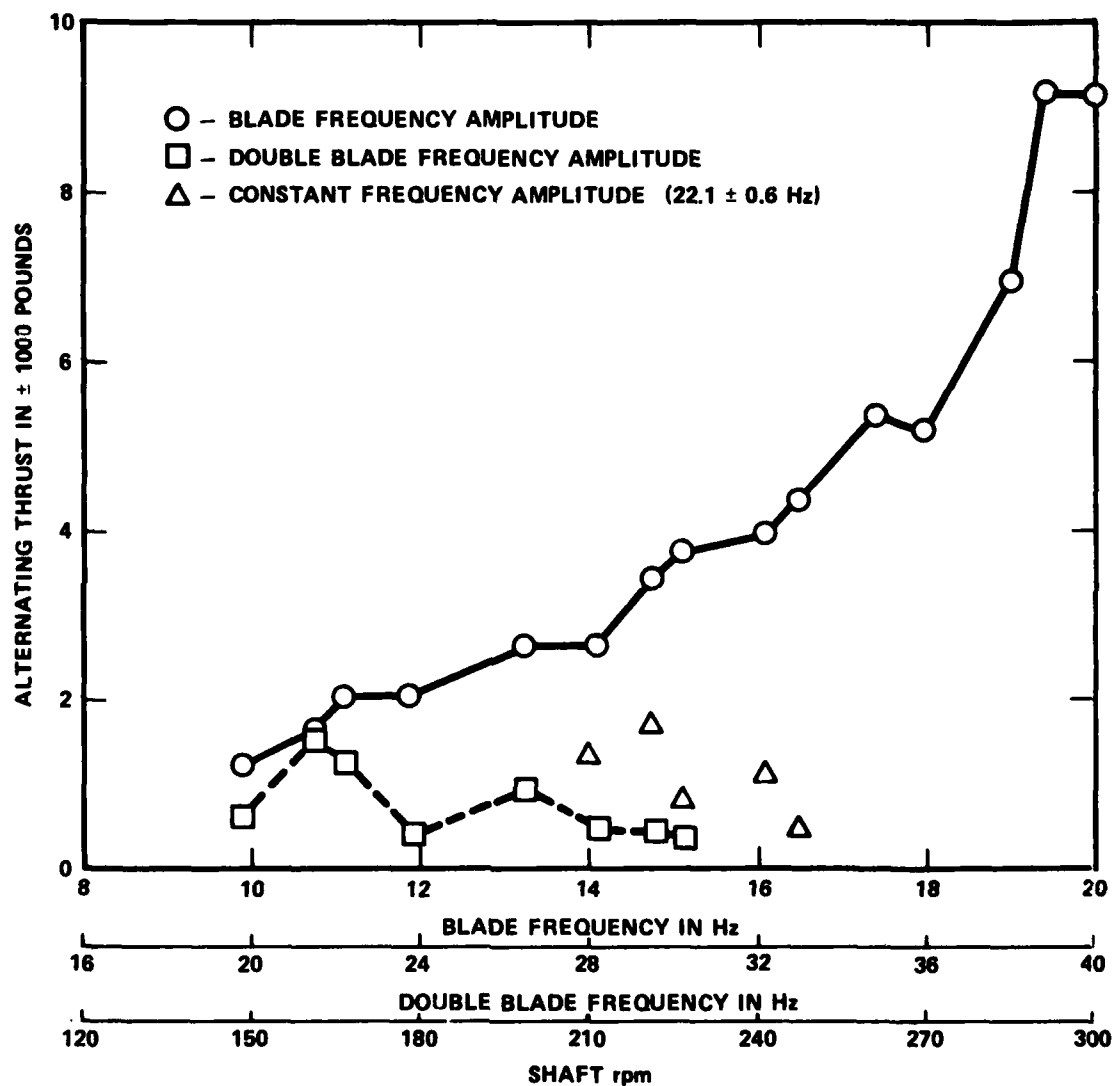
Figure 4 – Alternating Thrust Measured during Open Water,
Shaft Validation Test

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O – BLADE FREQUENCY AMPLITUDE
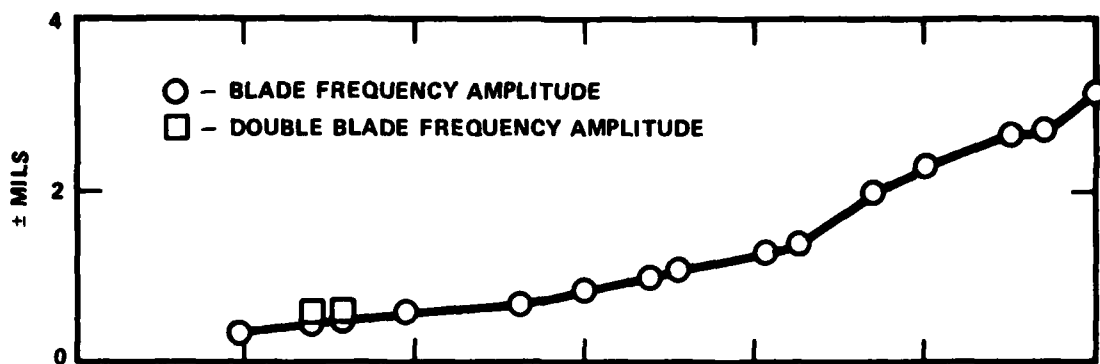□ – DOUBLE BLADE FREQUENCY AMPLITUDE

Figure 5a – Longitudinal
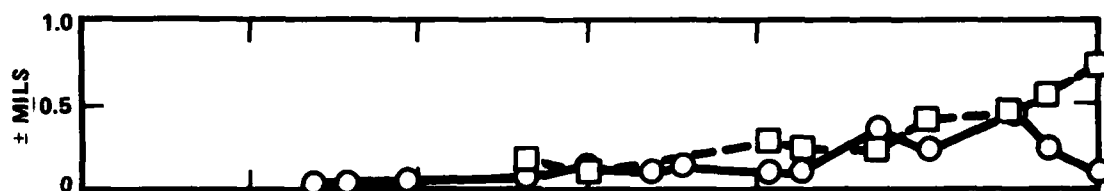
Figure 5b – Vertical
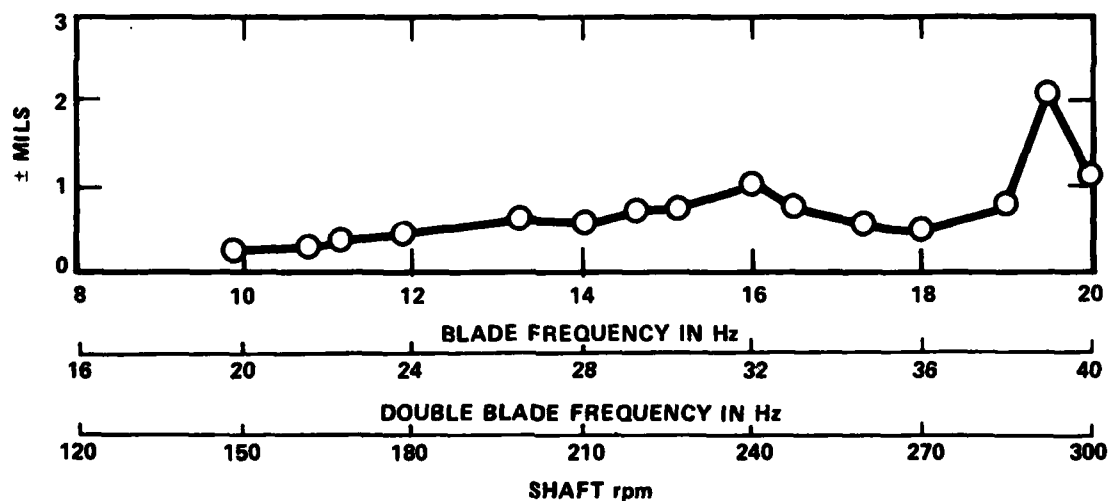
Figure 5c – Athwartship

Figure 5 – Thrustbearing Housing Vibratory Displacement Amplitudes
Measured during Open Water, Shaft Validation Test

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ALTERNATING THRUST
SCALE 1" = 32,945 POUNDS

ALTHWARTSHIP
ACCELERATION
THRUST BEARING
SCALE 1" = 0.116 g

LONGITUDINAL
ACCELERATION
THRUST BEARING
SCALE 1" = 0.485 g

1 sec.

Figure 6 – Oscillogram of Data Recorded during a Brash
Ice Maneuver, Run 4300

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Figure 7 - Histogram of Peak Alternating Thrust Amplitudes Measured during a Brash Ice Maneuver, Run 4300

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TABLE 1 – PROPULSION SYSTEM NAMEPLATE DATA

Thrustbearing

Waukesha Bearings Corporation
21-6×6 Pad Thrustbearings and
9×9 in. Journal Bearings

WBC Dwg. F 061-000-049
S.O. 1B28124   1026CA02
P.O. 1577F99N0101
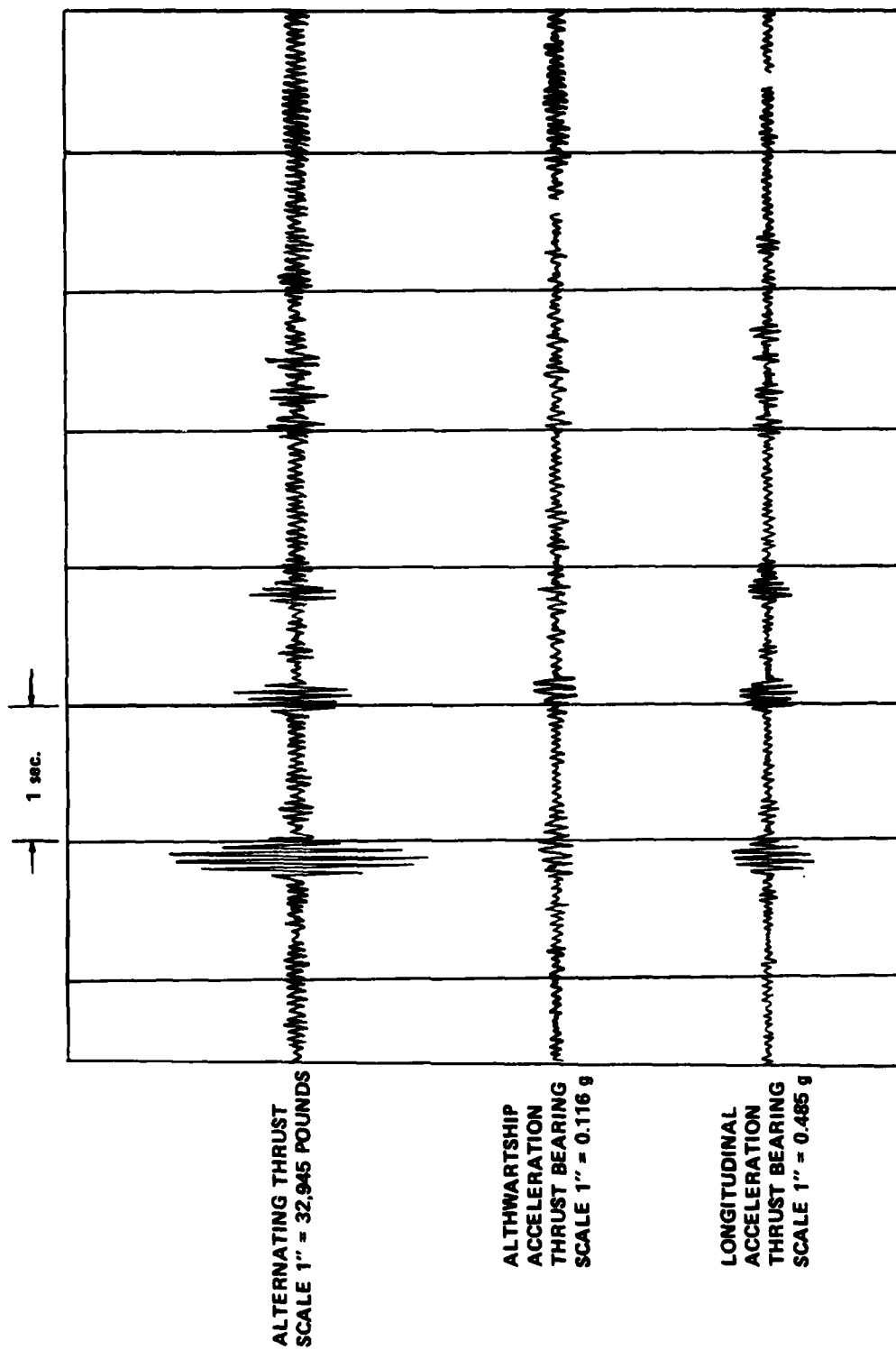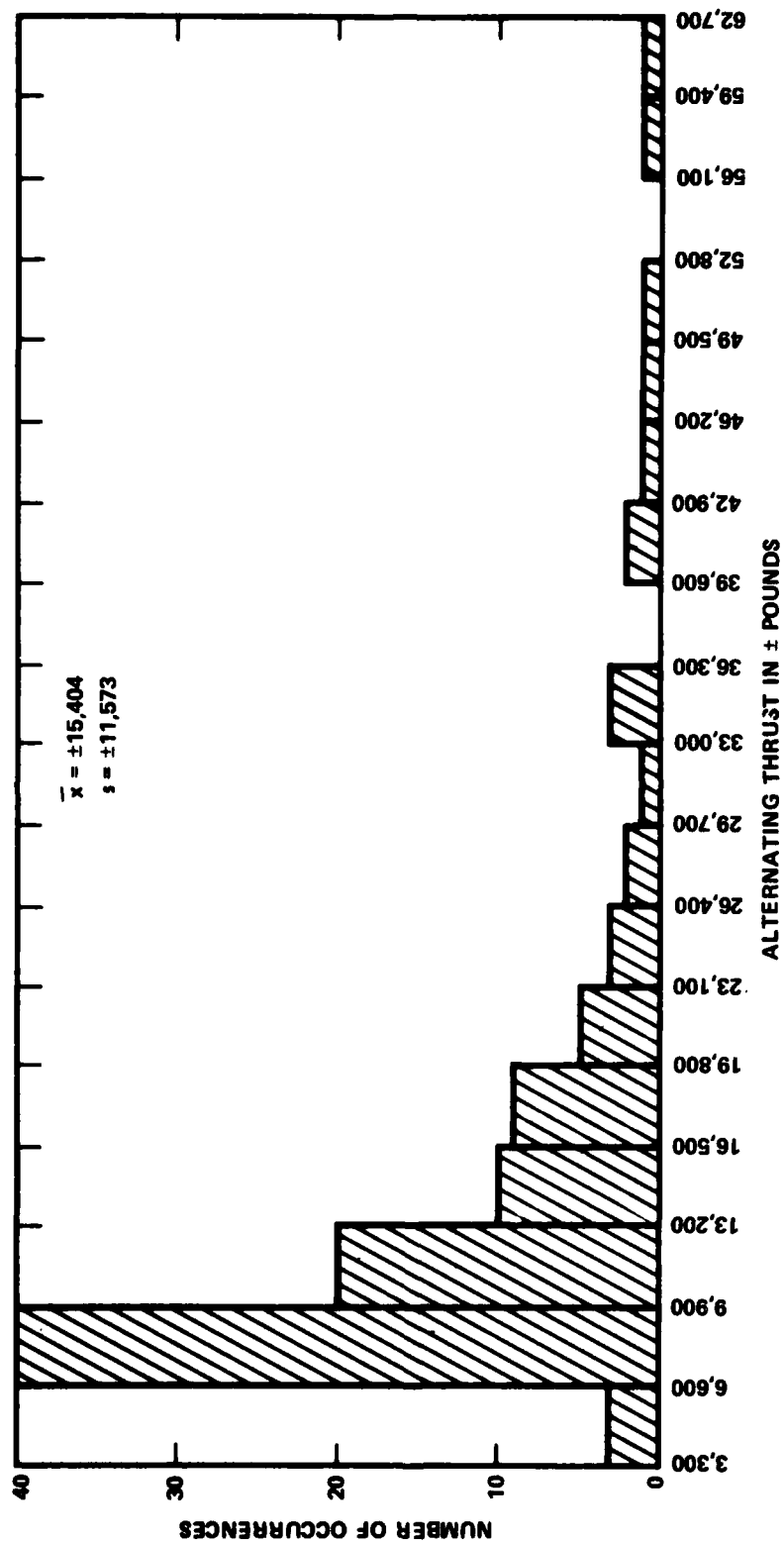Oil Viscosity = 300 S.S.V. at 100° F
Thrust Brng. End Float = 0.016 MIN.

Westinghouse d.c. Motor

2500 H.P.	d.c. Motor	rise const. 65° C
900 Volts		instr. book 102604
2220 Amps	1873B47H01	Ser. 10266402
245/305 RPM		

TABLE 2 – LIST OF SHAFT VALIDATION TEST INSTRUMENTATION

Number of Items	Model or Manufacturer	Item
3	Kistler 305T	Servo Accelerometers
1 rack	Kistler 515T	Servo Amplifier
1 rack	Ithaco P14	Filters
1 rack	Bur-Brown 1631/1632	Amplifiers
1	Brüel and Kjaer	FM Tape Recorder
1	CEC 5-124A	Oscillograph
1	Sony Tecktronix 323	Oscilloscope
1	Fluke 6750	Digital Voltmeter
1	Nicolet 440	Real Time Analyzer
1	HP 7035B	X-Y Plotter
1	HP 3310A	Function Generator

NOTES:

CEC – Consolidated Electrodynamics Corp.

HP – Hewlett Packard.

TABLE 3 - MAXIMUM VALUES MEASURED DURING OPEN WATER, SHAFT VALIDATION TEST

Run	Maneuver	Shaft (rpm)	Blade Frequency (Hz)	Propeller Shaft ③ Torque Mean (ft-lb)	Torque Alternating (± ft-lb)	Torque Percent = 100 × Alternating/Mean	Torsional Stress (± psi)	Thrust Mean (lb)	Thrust Alternating (± lb)	Thrust 100 × Alternating/Mean	Thrustbearing Housing Displacement (± mil) ③ Longitudinal	Vertical	Athwartship
10,140	Steady Speed	280	18.7										
10,150	Steady Speed	290	19.3										
10,160	Steady Speed	300	20.0	45,433	7,795	17.2	653	39,258	9,187	23.4	3.1	0.4	2.1
10,170	Full Left	300	20.0	①	6,326 ②	13.9	530	42,052	9,106	21.6	2.4 ②	0.9	
10,180	Full Right	300	20.0	①	10,149 ②	22.3	851				4.9 ②	1.2	
10,190	Full Left	300	20.0					①	5,271 ②	12.5	2.2 ②		2.1
10,200	Full Right	300	20.0	45,455				42,052	14,364	34.0	4.6 ②		2.3

NOTES:

① = value assumed same as run 10,200.

② = at natural frequency.

③ = at blade frequency unless noted otherwise.

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TABLE 4 - MAXIMUM VALUES MEASURED DURING SELECTED BRASH AND LEVEL ICE BREAKING MANEUVERS

Run	Ice Thickness (in.)	Maneuver	Shaft (rpm)	Blade Frequency (Hz)	Propeller Shaft ②						Thrustbearing Housing Displacement (mil) ②		
					Torque			Thrust					
					Mean (ft-lb)	Alternating (ft-lb)	Percent = 100×Alternating/Mean	Mean (lb)	Alternating (lb)	100×Alternating/Mean	Longitudinal	Vertical	Athwartship
4300		Brash Ice	292	19.5		28,725		46,420	60,948	131	16.2 ①	2.3	2.8
3210		Brash Ice	291	19.5	49,013	29,067 ①	59.3	49,599	32,286	65.1	12.6 ①	2.5 ①	1.8
1130	14	Ice Breaking	272	18.1	53,052	31,045	58.5				12.3 ①	2.3	
2120	14	Ice Breaking	249	16.6				42,747	27,015 ①	63.2	11.5 ①		3.3
1210	14	Ice Breaking	236	15.8				38,087	30,090 ①	79.0	10.8 ①		3.8

NOTES:

① = at natural frequency.

② = at blade frequency unless noted otherwise.

REFERENCES

1. Goodwin, M.J., LT et al., "Test Plan for 140' Cutter Test and Evaluation," United States Coast Guard Research and Development Center (2 Oct 1978).

2. "Vibration Analysis of Propulsion Motor, Shafting and Propeller of 140 Ft. WYTM Class Harbor Tug," Westinghouse Marine Division Engineering Report TN-046 (S.0.1-39V1424) (Jun 1977).

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